HEAT TRANSFER ENHANCEMENT USING NANOFLUIDS
An Overview

by

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Nanofluids are colloidal mixtures of nanometric metallic or ceramic particles in a base fluid, such as water, ethylene glycol or oil. Nanofluids possess immense potential to enhance the heat transfer character of the original fluid due to improved thermal transport properties. In this article, a brief overview has been presented to address the unique features of nanofluids, such as their preparation, heat transfer mechanisms, conduction and convection heat transfer enhancement, etc. In addition, the article summarizes the experimental and theoretical work on pool boiling in nanofluids and their applications.

Key words: *nanofluids, nanoparticles, pool boiling, heat transfer enhancement, applications of nanofluids.*

Introduction

Recent technological developments in the fields of electronics, transportation, medical and HVAC systems have resulted in a pressing need for a performance enhanced cooling system. Heat transfer by means of a flowing fluid in either laminar or turbulent regime or a stagnant fluid, is one of the most important processes in many industrial and civil applications. An effective cooling system can be achieved by intensifying the heat transfer process. Research and development activities are carried out to improve the heat transfer process to reduce the energy loss, which is an important task in this era of the great demand for energy. The heat transfer process can be improved by means of active and passive techniques. Active techniques like mechanical agitating, rotating, vibration and the use of electrostatic or magnetic fields are used successfully for heat transfer improvement. However, the requirement of an external energy input is costly and it is inconvenient under critical operations. Passive techniques include methods to modify the fluids' property, surface shape, roughness or external attachment to increase the surface area, and make the flow turbulent. However, conventional heat transfer fluids such as water, oil and ethylene glycol have an inherently poor thermal performance due to their low thermal conductivities. Figure 1 shows the solid metals, such as silver, copper, and iron and

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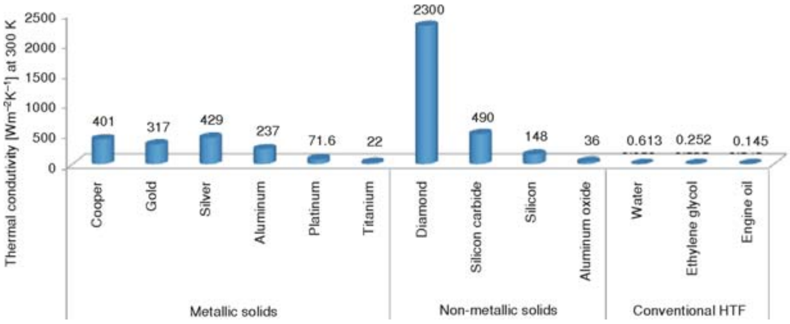

Figure 1. Thermal conductivity of materials [1]

non-metallic materials, such as alumina, CuO, SiC and carbon tubes that possess higher thermal conductivities than the conventional heat transfer fluids (HTF).

Maxwell [2] initiated a novel concept of dispersing solid particles in base fluids to break the fundamental limit of HTF having low thermal conductivities. Most of these earlier studies on this concept used millimeter or micrometer solid particles, which led to major problems such as rapid settling of the solid spherical particles in the fluids, clogging in micro channels and surface abrasion. In addition, the high pressure drop caused by these particles limited their practical applications.

The current and envisioned applications in such miniaturized devices call for special fluids to remove the heat as efficiently as possible. The miniaturization trend and modern nanotechnology provided an opportunity to process and produce particles with average crystallite sizes below 50 nm. Choi [3] conceived the novel concept of nanofluids by making use of these particle sizes in the order of 1 to 100 nm. Choi *et al*. [4] coined the term nanofluids. Nanofluids belong to a class of nanotechnology based heat transfer fluids produced by dispersing nanometer-sized particles in conventional heat transfer fluids along with a surfactant to increase their thermal stability. Compared with suspended conventional particles of milli or micro meter dimensions, nanofluids show better stability, high thermal conductivity with negligible pressure drop [5]. By suspending nanosized particles in heating or cooling fluids, the heat transfer performance of such fluids can be significantly improved. This is due to [6] the following:

- the suspended nanoparticles increase the surface area and heat capacity of the fluid,
- the suspended nanoparticles increase the effective thermal conductivity of the fluid,
- the interaction and collision among particles, fluids and the flow passage surface are intensified,
- the dispersion of nanoparticles flattens the transverse temperature gradient of the fluid in its flow passage,
- the pumping power is low when compared to that of pure fluids to achieve equivalent heat transfer enhancements, and
- there is reduced particle clogging when compared to conventional slurries.

Choi [7-9], Chon [10] and Eastman [11, 12] have attempted to suspend various metal and metal oxide nanoparticles in different base fluids. Nanoparticles have unique properties, such as large surface area to volume ratio, and lower kinematic energy which can be exploited in various applications. Nanoparticles are more better stable when dispersed in base fluids, due to their large surface area. Nanofluids are more stable when compared to micro or milli fluids which lead to many practical problems. Eastman [11, 24] reported that an increase in thermal conductivity was observed by adding only 0-3% of copper particles with 10 nm diameter in the base fluid ethylene glycol. Engineers now fabricate microscale devices such as microchannel heat exchangers and micropumps that are the size of dust specks. Further major advances would be obtained if the coolant flowing in the microchannels were to contain nanoscale particles to enhance heat transfer. Nanofluid technology will thus be an emerging and exciting technology of the twenty-first century [13].

Nanoparticles can be stably suspended in fluids with or without surfactants added to them. The experimental results of several research groups showed significant improvements in the heat transfer rates of nanofluids Boukines [14], Chen [15], Eastman [16], Kim [17], Said [18], Das [19, 21], Yang [20], Wen [22]. Das and Yang *et al*. reported the thermal conductivity enhancement of nanofluids and they show a temperature dependent characteristic increase of enhancement with rising temperature, which makes the nanoparticle more suitable for applications at high temperatures such as boiling. Low concentration of nano particle will increase the critical heat flux in a pool boiling systems. The nanoparticale coating of heating surface also enhances the CHF in pool boiling [23]. The improvements in heat transfer properties of nanofluids would enhance the rate of heat transfer, reduction in size of the systems, reduction in pump power and operational costs and provide much greater safety margins. The increase in viscosity is also very small when lower concentrations of nanoparticles are dispersed in base fluids.

Heat conduction mechanisms in nanofluids

Keblinski [25, 26] presented four possible mechanisms in nanofluids which may contribute to thermal conduction:

(1) Brownian motion of nanoparticles,
(2) liquid layering at the liquid/particle interface,
(3) ballistic nature of heat transport in nanoparticles, and
(4) nanoparticle clustering in nanofluids.

The Brownian motion of nanoparticles is too slow to directly transfer heat through a nanofluid; however, it could have an indirect role to produce a convection like micro environment around the nanoparticles and particle clustering to increase the heat transfer. This mechanism works well only when the particle clustering has both the positive and negative effects of thermal conductivity. The presence of an ordered interfacial liquid molecule layer is responsible for the increase in thermal conductivity.

Preparation of nanofluids

The preparation of nanofluids is the first key step in applying nanophase particles to change the heat transfer performance of conventional fluids. Nanofluids made from metals, oxides, carbides and carbon nanotubes can be dispersed in heat transfer fluids, such as water, ethylene glycol, hydrocarbons, and fluorocarbons with the addition of stabilizing agents. nanoparticles can be produced from several processes, such as gas condensation, mechanical attrition or chemical precipitation [22]. The particles can be produced under cleaner conditions and their surface can be protected from undesirable coatings during the gas condensation process. The main disadvantage of this method is that the particles processed by this technique occur with some agglomeration and its unsuitability to produce pure metallic nano powders.

The formation of agglomeration can be reduced to a good extent by using a direct evaporation condensation method [11, 21, 28, 29]. This method provides a very close control over particle size and produces particles for stable nanofluids without surfactants or electrostatic stabilizers, but has the disadvantage of oxidation of pure metals and low vapour pressure fluids.

There are four steps in the process of the direct evaporation – condensation method, or the one step method [11, 30]:

(1) a cylinder containing a heat transfer fluid, such as water or ethylene glycol is rotated so that a thin film of the fluid is constantly transported over the top of the chamber,
(2) a piece of the metallic material as the source of the nanoparticle is evaporated by heating on a crucible,
(3) the evaporated particles contact the fluid overhead and condense as a nanofluid, and
(4) the fluid is cooled at the base of the chamber to prevent any of its unwanted evaporation.

Another method of nanofluid synthesis is the laser ablation method, which has been used to produce alumina nanofluids [31]. Pure chemical synthesis is also an option which has been used by Patel [32] to prepare gold and silver nanofluids. Zhu *et al.* [33] also used a one-step pure chemical synthesis method to prepare nanofluids of copper nanoparticles dispersed in ethylene glycol. There are four guidelines for the synthesis of nanofluids. They are:

(1) dispersability of nanoparticles,
(2) stability of nanoparticles,
(3) chemical compatibility of nanoparticles, and
(4) thermal stability of nanofluids.

Conductive heat transfer enhancement with nanofluids

The oxide nanoparticles dispersed in water are the first batch of nanofluids that was investigated. Masuda *et al.* [34] dispersed Al_2O_3 nanoparticle of size 13 nm in diameter in water with a volume fraction up to 4.3%, and obtained an enhancement in thermal conductivity of up to 30%, and continued experiments with SiO_2 and TiO_2 of particle size 12 nm and 27 nm with maximum concentrations of up to 2.4 and 4.3%, and obtained thermal conductivity enhancement of up to 15-30%. Eastman *et al.* [30] also reported an enhancement of 30% in thermal conductivity with suspensions in water of Al_2O_3 nanoparticles with an average diameter of 33 nm and a volume fraction of 5%.

Wang *et al.* [35] dispersed Al_2O_3 of 8 nm particle size with water, Ethylene glycol, pump oil, and engine oil with different concentrations, resulting in the enhancement of 14-30%. Wang *et al.* [35] also dispersed CuO of 28 nm particle size in both water and ethylene glycol and predicted an enhancement of 35-55%. Lee *et al.* [36] also obtained similar results with CuO and Al_2O_3 nanoparticles dispersed both in water and ethylene glycol. Das *et al.* [19] dispersed Al_2O_3 and CuO in water and obtained a maximum enhancement of thermal conductivity of up to 25% and 36%, respectively. Wang *et al.* [37] studied the effects of the synthesis process on the thermal conductivity of water based nanofluids containing Al_2O_3 nanoparticles. They concluded that the dispersion techniques have no obvious effect on the measured thermal conductivity enhancements, while the addition of polymeric surfactants would decrease the thermal conductivity. The reason is that although the addition of surfactants makes nanoparticles better dispersed, the polymer molecules coating onto the surface of the nanoparticles actually increases the interfacial thermal resistance.

Besides Al_2O_3 and CuO, TiO_2 is also used as nanoparticles in nanofluids. Murshed *et al.* [38] measured the thermal conductivity of aqueous nanofluids containing both spherical and cylindrical TiO_2 particles. He found that nanofluids containing 15 nm spherical nanoparticles showed slightly lower enhancements than those containing 40 nm by 10 nm nanorods. As high as 33% enhancement was achieved in nanofluids containing nanorods. Pak *et al.* [39] dispersed

27 nm TiO_2 nanoparticles in water, and observed an enhancement of 10.7% in thermal conductivity for 4.35% of volume concentration, which is much lower than the enhancement of Al_2O_3 nanoparticles for the same concentration of solid particles. This is due to the fact that the thermal conductivity of Al_2O_3 is higher than that of TiO_2. It is observed from the experiments of Murshed *et al.* [38] and Pak *et al.* [39] that the enhancement of thermal conductivity increases with a decrease in particle size.

Metallic nanoparticles have a much higher thermal conductivity than oxides. Therefore at the same concentration of nanoparticles, much higher enhancements can be obtained than those of oxide nanofluids. A comparatively less number of studies were conducted on nanofluids containing oxide nanoparticles. But the results obtained were quite encouraging. Eastman [30] observed 45% increase in thermal conductivity for 0.0555% of volume concentration of Cu nanoparticle of 35 nm diameter when mixed in pump oil, and also found 40% enhancement for 0.2% of volume concentration of Cu nanoparticles of 10 nm diameter, when mixed with ethylene glycol [11]. Xuan *et al.* [6] conducted experiments using copper nanoparticles of the same diameter and concentration, which when mixed with water and transformer oil and the result was found to have an enhancement of 75% and 45%, respectively.

Jang *et al.* [27] proposed a theoretical model that involves the following four modes contributing to energy transfer for enhancing the thermal conductivity of nanofluids:

(1) collision between the base fluid molecules,
(2) thermal diffusion in nanoparticles,
(3) collision of nanoparticles with each other due to the Brownian motion, and
(4) collision between the base fluid molecules and nanoparticles by thermal induced fluctuations.

Patel *et al.* [32] measured the thermal conductivity of nanofluids containing gold and silver nanoparticles. The enhancement in thermal conductivity has been observed to increase as the temperature rises. At a temperature of 60 °C the enhancement in thermal conductivity was found to be 8.8% in toluene nanofluids with 0.011% of volume concentration of Au nanoparticles. Silver nanofluids exhibit a lesser thermal conductivity enhancement than gold nano-fluids, although silver has a higher thermal conductivity than gold. Thermal conductivity of nanofluid increases with increasing particle volume fraction except water-based fullerene nanofluid which has lower thermal conductivity than base fluid due to its lower thermal conductivity, 0.4 W/mK. In addition of fullerene in oil, the extreme pressure of nanofluids increases up to 225%. Stability of nanofluid is influenced by the characteristics between base fluid and suspended nanoparticles [40]. Vajjha *et al.* [41] showed the variation in the measured thermal conductivity of Al_2O_3 nanofluids with the particle volumetric concentration and temperature. Also, based on the polynomial approach of Yaws [41] which was applied to many industrial applications, they developed an empirical model which included the dependence of temperature and concentration in the following form:

$$k_{\mathrm{nf}}(\phi, T) = A(\phi) + B(\phi)T + C(\phi)T^2 \tag{1}$$

The coefficients *A*, *B*, and *C* are the polynomial functions of concentration ϕ and are listed in [41]. Hong [42, 43] dispersed 10 nm Fe nanoparticles in ethylene glycol and measured the thermal conductivity enhancement. It was found that for 0.55% volume concentration approximately an increase of 18% of thermal conductivity was observed. Theoretical and experimental studies have already disclosed that CNT (carbon nanotubes) have longitudinal thermal conductivities of more than 3000 W/mK, close to that of diamond, and over an order of magnitude higher than that of oxides and metals, Berber [44], Che [45], Ruoff [46]. Because of their low density, high aspect ratio and easy availability, CNT have a wide range of applications. Biercuk *et al.* [47] reported 70% enhancement in thermal conductivity in their industrial epoxy, by adding 1% weight of unpurified SWCNT (single walled carbon nanotubes), and they attributed the abnormal rise to the high thermal conductivity and high aspect ratio of the CNT. Xie *et al.* [48] dispersed spherical SiC particles with an average diameter of 26 nm, and cylindrical SiC particles with an average diameter of 600 nm into distilled water and ethylene glycol separately, with up to 4.2% volume concentrations. For SiC with 26 nm nanoparticles dispersed in distilled water, the thermal conductivity was enhanced by 22.9%. It is clearly observed that the thermal conductivity is enhanced at a higher percentage for higher particle size. Figure 3 shows the effect of the volume concentration of Al_2O_3 particles on nanofluid thermal conductivity enhancement. The effect of nanofluid temperature and particle size is also shown in fig. 3. It is clearly seen that the enhancement increases with increased volume concentration. Similarly, fig. 2 shows the effect of the volume concentration of CuO particles on nanofluid thermal conductivity enhancement.

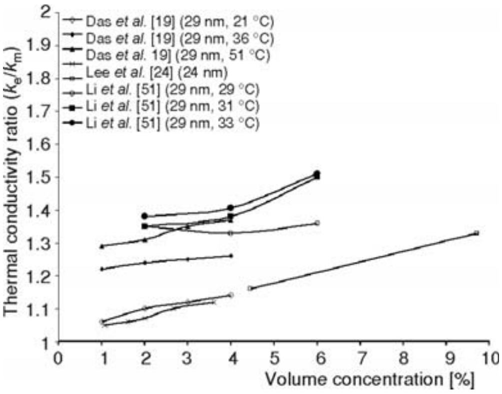

Figure 2. Enhancement of thermal conductivity of Al_2O_3 in water

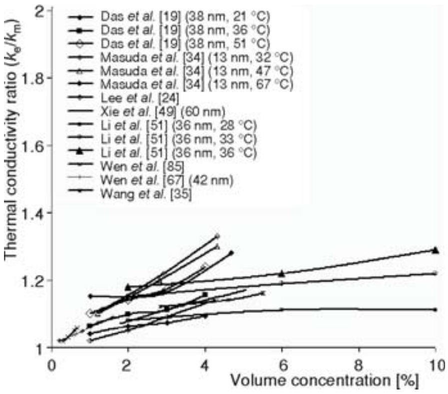

Figure 3. Enhancement of thermal conductivity of CuO in water

The maximum measured thermal conductivity enhancement for nanofluids containing nanoparticles and carbon nanotubes (CNT) is summarized in tab. 1.

Table 1. Summary of the maximum measured thermal conductivity enhancement for nanofluids containing nanoparticles

Reference	Base fluid	Nanoparticle	Size of nanoparticle	Maximum concentration [vol.%]	Maximum enhancement in *k* [%]
Masuda *et al.* [34]	Water	$A1_2O_3$	13 nm	4.3	30
Eastman *et al.* [30]	Water	$A1_2O_3$	33 nm	5	30
	Water	CuO	36 nm	5	60
	Pump oil	Cu	35 nm	0.055	45
Pak *et al.* [39]	Water	$A1_2O_3$	13 nm	4.3	32
	Water	TiO_2	27 nm	4.35	10.7

→

Table 1. Continuation

Reference	Base fluid	Nanoparticle	Size of nanoparticle	Maximum concentration [vol.%]	Maximum enhancement in *k* [%]
Wang *et al.* [35]	Water	$A1_2O_3$	28 nm	4.5	14
	Ethylene glycol	$A1_2O_3$	28 nm	8	40
	Pump oil	$A1_2O_3$	28 nm	7	20
	Engine oil	$A1_2O_3$	28 nm	7.5	30
	Water	CuO	23 nm	10	35
	Ethylene glycol	CuO	23 nm	15	55
Lee *et al.* [36]	Water	$A1_2O_3$	24.4 nm	4.3	10
	Ethylene glycol	$A1_2O_3$	24.4 nm	5	20
	Water	CuO	18.6 nm	4.3	10
	Ethylene glycol	CuO	18.6 nm	4	20
Das *et al.* [19]	Water	$A1_2O_3$	38 nm	4	25
	Water	CuO	28.6 nm	4	36
Xie *et al.* [49]	Water	$A1_2O_3$	60 nm	5	20
	Ethylene glycol	$A1_2O_3$	60 nm	5	30
	Pump oil	$A1_2O_3$	60 nm	5	40
Prasher *et al.* [50]	Water	$A1_2O_3$	10 nm	0.5	100
Krishnamurthy *et al.* [53]	Water	$A1_2O_3$	20 nm	1	16
Liu *et al*. [54]	Ethylene glycol	CuO	25 nm	5	22.4
Murshed *et al.* [38]	Water	TiO_2	15 nm	5	33
Xuan *et al.* [6]	Water	Cu	100 nm	7.5	75
	Transformer oil	Cu	100 nm	7.5	45
Eastman *et al.* [11]	Ethylene glycol	Cu	10 nm	0.2	40
Patel *et al.* [32]	Toluene	Au	15 nm	0.011	8.8
	Water	Au	15 nm	0.00026	8.3
	Water	Ag	70 nm	0.001	4.5
Hong *et al.* [42, 43]	Ethylene glycol	Fe	10 nm	0.55	18
Choi *et al.* [8]	PAO	MWCNT	–	1	160
Xie *et al.* [55]	Water	MWCNT	–	1	6
	Ethylene glycol	MWCNT	–	1	12
	Decene	MWCNT	–	1	20
Wen *et al.* [56]	Water	MWCNT	–	0.84	21
Yang *et al.* [57]	PAO	MWCNT	–	0.35	200
Assael *et al.* [58, 59]	Water	DWCNT	–	1	8
	Water	MWCNT	–	0.6	34
Liu *et al.* [60]	Synthetic oil	MWCNT	–	2	30
	Ethylene glycol	MWCNT	–	1	12.4

The findings reported that the particle size, nature of material, operating temperature, thermal conductivity, and the pH value of base fluids, all have an influence on the thermal conductivity enhancement in nanofluids. Das *et al.* [19, 21] was the first group to study the temperature dependence of thermal conductivity in nanofluids. By varying the temperatures from 21 °C to 51 °C of nano fluid produced by dispersing Al_2O_3 nanoparticles of a diameter 38 nm in water, and by varying the concentrations from 1 to 4%, they observed that with a rise in temperature, the enhancement in thermal conductivity increased linearly depending on the concentration of nanoparticle. Xie *et al.* [49] concluded that the pH value of the base fluid as well as the nanoparticle size affects the thermal conductivity enhancement of Al_2O_3 dispersed in water, ethylene glycol and pump oil.

Phrasher *et al.* [50] found the maximum enhancement of 100% at 85 °C for 10 nm Al_2O_3 particles dispersed in water at a volume concentration of 0.5%, much higher than the results reported by the other researchers and this result was due to the small size of the Al_2O_3 nanoparticles and the higher temperatures. Li *et al.* [51] dispersed CuO and Al_2O_3 nanoparticles with a diameter of 29 nm and 36 nm in distilled water at different concentrations from 2% to 10%. The thermal properties were measured at temperatures from 27.5 °C to 34.7 °C. Their results showed that the thermal conductivity of the nanoparticles, the particle size, volume fraction and temperature had a significant impact on the thermal conductivity of the nanofluid.

At 34 °C, a 6% volume concentration of CuO nanoparticles dispersed in water enhanced the thermal conductivity, which is 1.52 times that of pure distilled water, while a nanofluid with 10% Al_2O_3 nanoparticles increased the thermal conductivity by a factor of 1.3. Based on their results they suggested that the thermal conductivity enhancement in nanofluid could be described by the equation for Al_2O_3 in water:

$$\frac{k_{\mathrm{EMT}} - k_{\mathrm{f}}}{k_{\mathrm{f}}} = 0.764481\phi + 0.0186886T - 0.4624147175 \tag{2}$$

and for CuO in water:

$$\frac{k_{\mathrm{EMT}} - k_{\mathrm{f}}}{k_{\mathrm{f}}} = 3.76108\phi + 0.017924T - 0.30734 \tag{3}$$

Figures 4 and 5 show the increase in thermal conductivity based on temperature for Al_2O_3 and CuO in water. From these graphs, it is clearly observed that the thermal conductivity

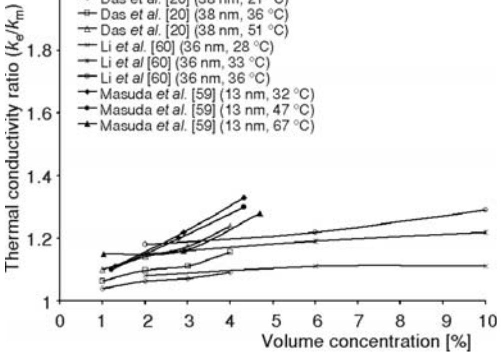

Figure 4. Temperature dependent thermal conductivity of alumina in water

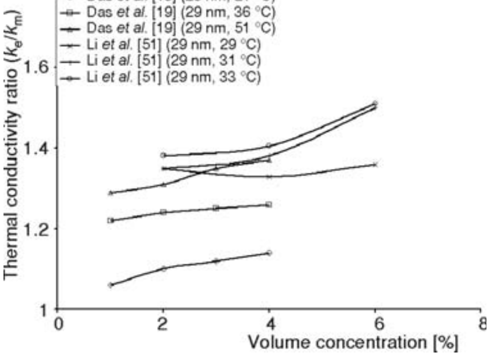

Figure 5. Temperature dependent thermal conductivity of CuO in water

is enhanced with an increased volume fraction of the nanoparticle. Figure 6 shows the comparison of the metallic nanoparticles with oxide nanoparticles, with different range of particle size in ethylene glycol. It is observed that nanofluids with copper and iron nanoparticles show a good increase in thermal conductivity even at very low concentrations when compared with oxide nanofluids. Figures 7 and 8 represent the enhancement for different nanofluids with higher particle size. From figs. 6 and 7, the oxide nanofluids show a good enhancement at low concentration when compared with small sized metallic nanoparticles. Kumar *et al.* [52] have developed a theoretical model to account for the thermal conductivity enhancement in nanofluids. The strong temperature dependence was modeled by taking the particle size, concentration, and temperature into consideration. Theoretical predictions agreed with the experimental data on the thermal conductivity measurement of nanofluids.

Mintsa *et al.* [61] developed an effective thermal conductivity measurement of alumina/water and copper oxide/water nanofluids. The effects of particle volume fraction, temperature and particle size were investigated. Readings at ambient temperature as well as over a relatively large temperature range were made for various particle volume fractions of up to 9%. The results clearly show that an overall increase in the effective thermal conductivity is predicted with an increase in the particle volume fraction and with a decrease in particle size. The enhancement of thermal conductivity influenced by a change in temperature is summarized in tab. 2.

Convective heat transfer enhancement with nanofluids

Li *et al.* [64] and Xuan *et al.* [65] presented an experimental system to investigate the convective heat transfer coefficient and friction factor of nanofluids for laminar and turbulent flows in a tube. The working fluid used was 100 nm Cu particles dispersed in deionized water.

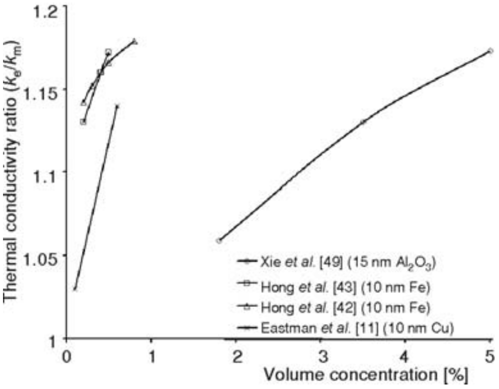

Figure 6. Effect of metallic nanoparticles in ethylene glycol

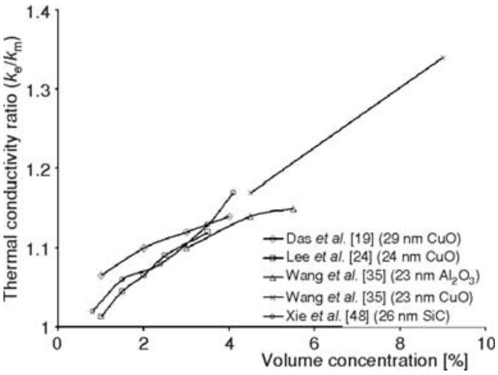

Figure 7. Effect of particle material for nanoparticles in water

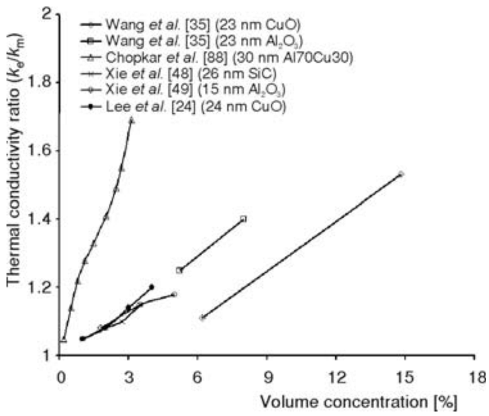

Figure 8. Effect of particle material for nanoparticles in ethylene glycol

Table 2. Enhancement of thermal conductivity influenced by change in temperature

Reference	Basefluid	Nanoparticle	Temperature	Size on nanoparticle	concentration [vol.%]	Enhancement ratio of *k* [%]
Masuda *et al.* [34]	Water	$A1_2O_3$	31.85 ºC	13	1.3-4.3	1.109-1.324
			46.85 ºC	13	1.3-4.3	1.1-1.296
			66.85 ºC	13	1.3-4.3	1.092-1.262
	Water	SiO_2	46.85 ºC	12	1.1-2.3	1.01-1.011
			66.85 ºC	12	1.1-2.4	1.005-1.007
	Water	TiO_2	31.85 ºC	27	3.25-4.3	1.08-1.105
			46.85 ºC	27	3.25-4.3	1.084-1.108
			86.85 ºC	27	3.1-4.3	1.075-1.099
Das *et al.* [19]	Water	$A1_2O_3$	21 ºC	38.4	1-4	1.02-1.09
			36 º C	38.4	1-4	1.07-1.16
			51 º C	38.4	1-4	1.10-1.24
	Water	CuO	21	28.6	1-4	1.07-1.14
			36	28.6	1-4	1.22-1.26
			51	28.6	1-4	1.29-1.36
Patel *et al.* [32]	Water	Citrate reduced Ag	30	60-70	0.001	1.03
			60	60-70	0.001	1.04
	Water	Citrate reduced Ag	30	10-20	0.00013	1.03
Patel *et al.* [32]	Water	Citrate reduced Au	60	10-20	0.00013	1.05
			30	10-20	0.00026	1.05
			60	10.-20	0.00026	1.08
	Toluene	Thiolate covered	30	3-4	0.005	1.03
			60	3-4	0.005	1.05
			30	3-4	0.008	1.06
			60	3-4	0.008	1.07
			30	3-4	0.011	1.06
			60	3-4	0.011	1.09
Chon *et al.* [10]	Water	Al_2O_3	21	11	1	1.09
			71	11	1	1.15
			21	47	1	1.03
			71	47	1	1.1
			21	150	1	1.004
			71	150	1	1.09
			21	47	4	1.08
			71	47	4	1.29

→

Table 2. Continuation

Reference	Basefluid	Nanoparticle	Temperature	Size on nanoparticle	concentration [vol.%]	Enhancement ratio of *k* [%]
Ding *et al.* [62]	Water	MWCNT+ gum arabic	20	–	0.05-0.49	1.00-1.10
			25	–	0.05-0.49	1.07-1.27
			30	–	0.05-0.49	1.18-1.79
Li *et al.* [51]	Water	Al_2O_3	27.5	36	2-10	1.08-1.11
			32.5	36	2-10	1.15-1.22
			34.7	36	2-10	1.18-1.29
	Water	CuO	28.9	29	2-6	1.35-1.36
			31.3	29	2-6	1.35-1.50
			33.4	29	2-6	1.38-1.51

Experiments with different concentrations of nanoparticles were conducted. The Reynolds number of the nanofluids varied in the range of 800-25000. The experimental results concluded that the convective heat transfer coefficient of the nanofluids varied with the flow velocity and volume fraction. Also, the values were higher than those of the base fluid in the same conditions. The Nusselt number of the nanofluids with 2% volume fraction of Cu particles was 60% higher than that of water. The results are shown in fig. 9.

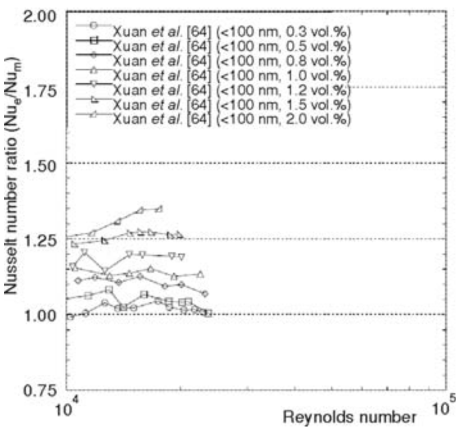

Figure 9. Turbulent flow heat transfer of Cu in water [63]

From the experimental data of Xuan *et al.* [64] and Li, *et al.* [65], the new heat transfer correlations for the prediction of the heat transfer coefficient of nanofluids flowing in a tube were given as follows:

- for laminar flow

$$\mathrm{Nu}_{\mathrm{nf}} = 0.4329[1.0 + 11.285\phi^{0.754}\mathrm{Pe}_{\mathrm{d}}^{0.218}]\mathrm{Re}_{\mathrm{nf}}^{0.333}\,\mathrm{Pr}_{\mathrm{nf}}^{0.4} \tag{4}$$

- for turbulent flow

$$\mathrm{Nu}_{\mathrm{nf}} = 0.0059[1.0 + 7.6286\phi^{0.6886}\mathrm{Pe}_{\mathrm{d}}^{0.001}]\mathrm{Re}_{\mathrm{nf}}^{0.9233}\,\mathrm{Pr}_{\mathrm{nf}}^{0.4} \tag{5}$$

where

$$\mathrm{Pe}_{\mathrm{d}} = \frac{u_{\mathrm{m}} d_{\mathrm{p}}}{\alpha_{\mathrm{nf}}}; \quad \mathrm{Re}_{\mathrm{nf}} = \frac{u_{\mathrm{m}} D}{\nu_{\mathrm{nf}}}; \quad \mathrm{Pr}_{\mathrm{nf}} = \frac{\nu_{\mathrm{nf}}}{\alpha_{\mathrm{nf}}}$$

$$\alpha_{\mathrm{nf}} = \frac{k_{\mathrm{nf}}}{(\rho C_p)_{\mathrm{nf}}} = \frac{k_{\mathrm{nf}}}{(1-\phi)(\rho C_p)_{\mathrm{f}} + \phi(\rho C_p)_{\mathrm{d}}}$$

The results indicated that the friction factor of the nanofluids was equal to that of water under some working conditions, and did not vary with volume fraction. This shows that the nanofluid did not increase the pump power. The friction factor of the nanofluids was determined from the following equation:

$$\lambda_{\mathrm{nf}} = \frac{\Delta p_{\mathrm{nf}} D}{\dfrac{L^2 \mathrm{g}}{u_{\mathrm{m}}^2}} \tag{6}$$

Heris *et al.* [66] performed experiments with Al_2O_3 and CuO nanoparticles in water under laminar flow up to turbulence. They found more heat transfer enhancement, as high as 40%, with Al_2O_3 particles, while the thermal conductivity enhancement was less than 15%. The Dittus Boelter equation was not valid for the prediction of the Nusselt number of the nanofluids at various volume fractions. The results are shown in figs. 10 and 11.

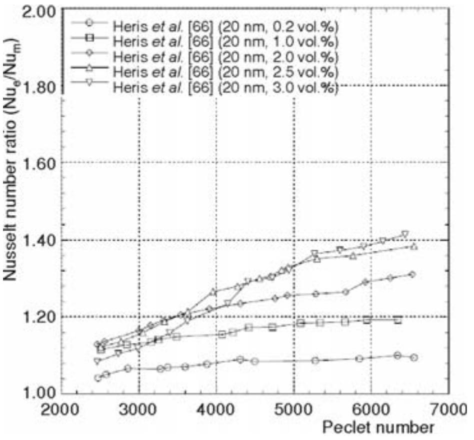

Figure 10. Laminar flow heat transfer of Al_2O_3 in water [63]

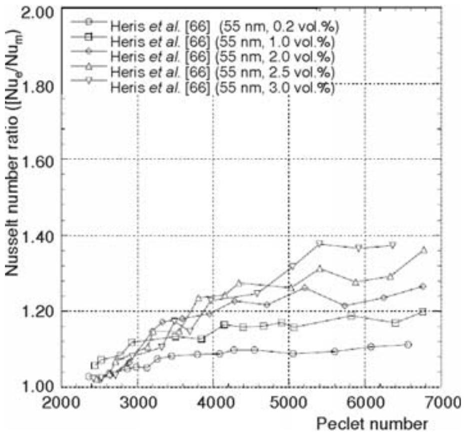

Figure 11. Laminar flow heat transfer of CuO in water [63]

Wen *et al.* [67] conducted an experimental study to evaluate the convective heat transfer coefficient of the γAl_2O_3 nanoparticles suspended in deionized water for laminar flow in a copper tube, considering the entrance region. The experiment was conducted at constant wall heat flux under various concentrations of nanoparticles. The experimental set-up consists of a straight copper tube; sodium dodecylbenzene sulfonate (SDBS) was used as a dispersant to stabilize the nanoparticles. From the results it was clearly observed that the local heat transfer coefficient varied with the Reynolds number and volume fraction. Further, the thermal boundary layer thickness decreased with an increase in the heat transfer coefficient.

The experimental results of Yang *et al.* [68] illustrated the convective heat transfer coefficient of graphite nanoparticles dispersed in liquid for laminar flow in a horizontal tube heat exchanger. Yang *et al.* focused on an aspect ratio (*l/d*) of about 0.02 almost like a disc, because the addition of large aspect ratio particles into a fluid may increase its viscosity compared with the single phase. The overall heat transfer resistance relationship is used to determine the heat transfer coefficient of the nanofluids, h_{nf}:

$$\frac{1}{U_{\mathrm{o}}} = \frac{1}{h_{\mathrm{nf}}}\left(\frac{A_{\mathrm{i}}}{A_{\mathrm{o}}}\right) + \frac{D_{\mathrm{o}}}{2k}\ln\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right) + \frac{1}{h_{\mathrm{o}}} \tag{7}$$

The overall heat transfer coefficient can be determined from:

$$U_{\mathrm{o}} = \frac{Q}{A_{\mathrm{o}} \Delta T_{\mathrm{m}}} \tag{8}$$

The Monrad and Pelton's equation for turbulent flow in annuli was used to calculate the outside heat transfer coefficient, h_{o} as follows:

$$\mathrm{Nu} = 0.020\,\mathrm{Re}^{0.8}\,\sqrt[3]{\mathrm{Pr}}\left(\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)^{0.53} \tag{9}$$

From the results shown in figs. 12 and 13, it is confirmed that the heat transfer coefficient increased with the Reynolds number, with a maximum of Re = 80. The increase in fluid temperature leads to small improvements in the heat transfer enhancement of nanofluids. One of the reasons is the rapid alignment of nanoparticles in less viscous fluid, leading to less contact between the nanoparticles. The second factor is that depletion of particles in the near wall fluid could lead to a lower thermal conductivity layer near the wall. Graphite nanoparticles in different base fluids gave different heat transfer coefficients. This may be due to particle shape, morphology or surface treatment. This means that one type of nanoparticle is more effective than another in augmenting the heat transfer coefficient of the nanofluids. The experimental data were used to develop a new heat transfer correlation for the prediction of the heat transfer coefficients of laminar flow nanofluids in a more convenient form by modifying the Seider Tate equation to incorporate two constants, *a* and *b*, to give the form:

$$\Omega = a\mathrm{Re}^{b} \tag{10}$$

$$\Omega = \mathrm{Nu}\,\mathrm{Pr}^{-1/3}\,\sqrt[3]{\frac{L}{D}\left(\frac{\mu_{\mathrm{b}}}{\mu_{\mathrm{w}}}\right)^{-0.14}} \tag{11}$$

Khanafar [69] performed a numerical study of buoyancy-driven heat transfer in a two dimensional enclosure. Kim *et al.* [70] analytically investigated the connective instability driven by the buoyancy and heat transfer characteristics of nanofluids. They proposed a factor

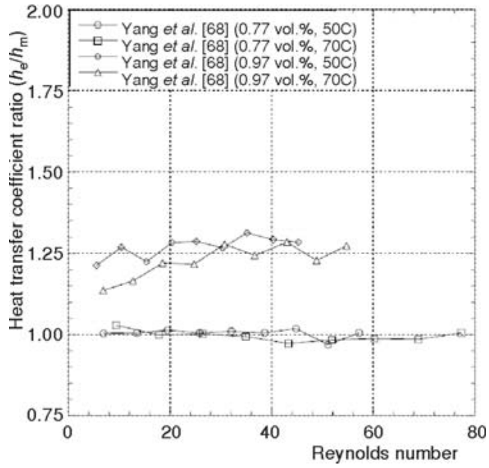

Figure 12. Laminar flow heat transfer: graphite particles in transmission fluid [63]

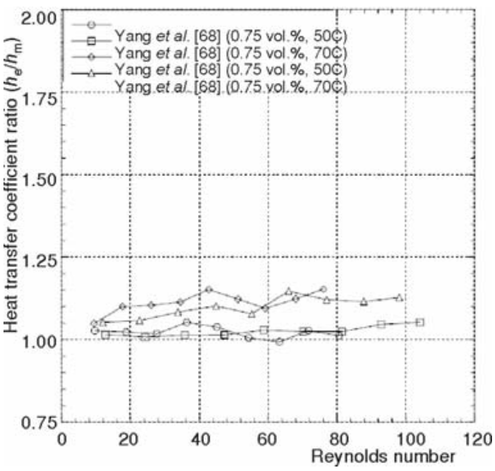

Figure 13. Laminar flow heat transfer of graphite in synthetic oil mixture [63]

that describes the effect of nanoparticle addition on the convective instability and heat transfer characteristics of a base fluid. From the results it was concluded that as the density and heat capacity of the nanoparticles increase, the thermal conductivity and shape factor of nanoparticles decreases, and the convective motion in a nanofluid sets in easily.

Rea *et al.* [71] investigated laminar convective heat transfer and viscous pressure loss for alumina-water and zirconia-water nanofluids in a flow loop with a vertical heated tube. The heat transfer coefficients in the entrance region and in the fully developed region are found to increase by 17% and 27%, respectively, for alumina-water nanofluids at 6 vol % with respect to pure water. The zirconia-water nanofluids' heat transfer coefficient increases by approximately 2% in the entrance region and 3% in the fully developed region at 1.32 vol.%. The measured pressure loss for the nanofluids is, in general, much higher than for pure water. However, both the measured nanofluids' heat transfer coefficient and pressure loss are in good agreement with the traditional model predictions for laminar flow, provided the loading and temperature dependent thermo physical properties of the nanofluids are utilized in the evaluation of the dimensionless numbers. In other words, no abnormal heat transfer enhancement or pressure loss was observed within the measurement errors.

Gherasim *et al.* [72] experimentally investigated the heat transfer enhancement capabilities of coolants with suspended nanoparticles (Al_2O_3 in water) inside a radial flow cooling device. The steady laminar radial flow of nanofluids between a heated disk and a flat plate with axial coolant injection has been considered. From the results it is confirmed that the heat transfer is enhanced with the use of this type of nanofluids. The Nusselt number was found to increase with particle volume fraction, and the Reynolds number and a decrease in disc spacing. The results also indicate that, for the considered range of Reynolds number and particle volume fractions, the specific heat models used do not significantly influence the results obtained.

Torii [73] studied the forced convective heat transport phenomenon of nanofluids inside a horizontal circular tube subjected to a constant and uniform heat flux at the wall, to study the effect of the inclusion of nanoparticles on heat transfer enhancement, thermal conductivity, and viscosity and pressure loss in the turbulent flow region. From the results he has concluded that, the heat transfer enhancement is caused by the suspended nanoparticles, and it becomes more pronounced with the increase of the particle volume fraction. Its augmentation is reported for three different nanofluids, and it is observed that the presence of particles produces adverse effects on viscosity and pressure loss, and these increases with the particle volume fraction. Although various conjectures have been proposed to explain the abnormal increase in thermal conductivity of nanofluids, the detailed mechanism has not been fully understood and explained. The main reason is due to the lack of knowledge of the most fundamental factor governing the mechanisms such as Brownian motion, liquid layering, phonon transport, surface chemical effects, and agglomeration. Applying a surface complexation model for the measurement data of hydrodynamic size and thermal conductivity, Lee *et al.* [87] have shown that surface charge states are mainly responsible for the increase in the present condition and may be the factor incorporating all the mechanisms as well.

Pool boiling in nanofluids

Phase-change processes are important in thermal power plants and chemical industries where the heat flux requirements are large. The two-phase heat transfer-boiling and condensation, calls for a very large amount of rate of the heat transfer during its phase change. However, the discussion mainly pertains to pool boiling heat transfer. Bang *et al*. [76] obtained similar results from the pool boiling in Al_2O_3-water nanofluids. A 200% increase in CHF was observed on the measured pool boiling curves of nanofluids. The results are shown in fig. 14.

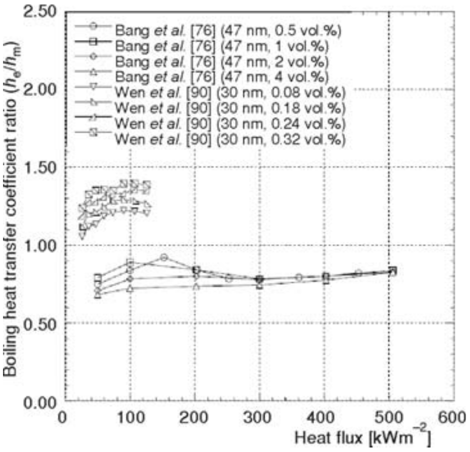

Figure 14. Pool boiling heat transfer of Al_2O_3 in water from a horizontal surface [63]

Bang *et al.* [77], in another experimental study on a smooth horizontal surface with alumina-water nanofluids, found that the heat transfer performance of these nanofluids is poor when compared with that of pure water in natural convection and nucleate boiling. You *et al.* [74] measured the critical heat flux (CHF) in the pool boiling of Al_2O_3-water nanofluids and found an unprecedented threefold increase in CHF over pure water at a mass fraction of nanopraticles as slow as 10^{-5}, when compared with the boiling in pure water, the average size of the bubbles increased while the frequency of bubbles decreased significantly. Vassallo *et al.* [75] confirmed You's results in nanofluids containing SiO_2. Two to three fold increase in CHF was observed.

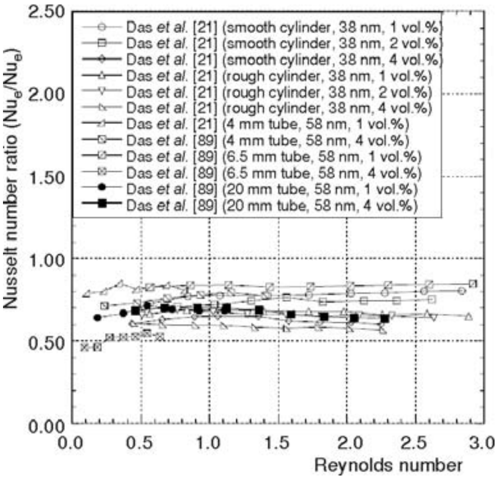

Figure 15. Pool boiling heat transfer of Al_2O_3 in water [63]

Das *et al.* [21] also reported that in the case of nanofluids, the natural convection stage continues relatively longer, and nucleate boiling is delayed. On the other hand, CHF has been enhanced in not only horizontal but also in vertical pool boiling. The results are shown in fig. 15. Das *et al.* [89] also conducted an experimental study of the pool boiling of Al_2O_3 in water nanofluids in a horizontal tube with a large diameter (20 mm). They showed the deterioration of the pool boiling performance of nano-fluids with increasing particle loading, and attributed this deterioration of the pool boiling not to the change of the fluid properties, but to the change of the tube surface characteristics of the nanoparticles trapped on the rough surface. The pool boiling enhancements are summarized in tab. 3.

Applications

Experimentally and theoretically Nanofluids have been shown to possess improved heat transport properties and higher energy efficiency in a variety of thermal exchange systems for different industrial applications, such as transportation, electronic cooling, military, nuclear energy, aerospace etc. Nanofluid research could lead to a major impact in developing next generation coolants for numerous engineering and medical applications. The above applications are stated and briefly discussed.

Table 3. Summary of pool boiling enhancements

Reference	Base fluid	Nano particle	Size of nanoparticle	Maximum concentration [vol.%]	Enhancement ratio	Geometry and surface condition
Das *et al.* [21]	Water	Al_2O_3	38	1.00	0.72-0.80	Smooth cylindrical surface
			38	2	0.69-0.76	
			38	4	0.6-0.65	
			38	1	0.65-0.69	Rough cylindrical surface
			38	2	0.64-0.69	
			38	4	0.57-0.6	
Das *et al.* [89]	Water	Al_2O_3	58.4	1	0.79-0.85	4 mm tube
			58.4	1	0.71-0.79	6.5 mm tube
			58.4	1	0.83-0.85	20 mm tube
			58.4	4	0.46-055	4 mm tube
			58.4	4	0.64-0.71	6.5 mm tube
			58.4	4	0.64-0.7	20 mm tube
Bang *et al.* [76]	Water	Al_2O_3	47	0.5	0.75-0.92	Horizontal surface
			47	1	1.78-0.89	Horizontal surface
			47	2	0.7-0.83	Horizontal surface
			47	4	0.68-0.83	Horizontal surface
Wen *et al.* [90]	Water	Al_2O_3	10-50	0.08	1.06-0.83	Horizontal surface
			10-50	0.18	1.12-1.29	Horizontal surface
			10-50	0.24	1.19-1.36	Horizontal surface
			10-50	0.32	1.24-1.4	Horizontal surface
You *et al.* [74]	Water	Al_2O_3		0-0.13	1.24-3.11	Horizontal surface
Vassallo *et al.* [75]	Water	SiO_2	15	0.5	1.6	Horizontal NiCr wire
			50	0.5	3	Horizontal NiCr wire
			3000	0.5	1.5	Horizontal NiCr wire
Liu *et al.* [86]	Water	CuO	50	0.02-0.32	1.75-1.25	Saturated, jet on horizontal surface
			50	0.02-0.32	1.16-1.25	Saturated, jet on horizontal surface

Heat transportation

The mixture of ethylene glycol and water is almost a universally used vehicle coolant due to its lowered freezing point as well as its elevated boiling point. The thermal conductivity of ethylene glycol is relatively low compared to that of water, while the engine oils are much worse heat transfer fluids than ethylene glycol in thermal transport performance. The addition of nanoparticles and nanotubes to these coolants and lubricants to form nanofluids can the increase their thermal conductivity, and give the potential to improve the heat exchange rates and fuel efficiency. The above improvements can be used to reduce the size of the cooling systems or remove the heat from the vehicle engine exhaust in the same cooling system. Tzeng *et al.* [79] have conducted research to study the effects of nanofluids in the cooling of automatic transmission. They dispersed CuO and Al_2O_3 nanoparticles and antifoam agents in the transmission fluid, and then, the transmission fluid was used in real time four wheel automatic transmissions. The results show that CuO nanofluids have the lowest temperature distribution at both high and low rotating speed and accordingly the best heat transfer effect.

Electronics cooling

The power dissipation of IC (integrated circuits) and micro electronic components has dramatically increased due to their size reduction. Better thermal management and cooling fluids with improved thermal transport properties are needed for safe operation. Nanofluids have been considered as working fluids in heat pipes for electronic cooling application. Tsai *et al.* [80] were probably the first to show experimentally that the thermal performance of the heat pipe can be enhanced when nanofluids are used. Gold nanoparticles with a particle size of 17 nm dispersed in water were used as a working fluid in a disk shaped miniature heat pipe. The result shows that the thermal resistance of the disk shaped miniature heat pipe is reduced by nearly 40% when nanofluids are used instead of de-ionized (DI) water. Kang *et al*. [81] measured the temperature distribution and thermal resistance of a conventional grooved circular heat pipe with water based nanofluids containing 1 to 50 ppm of 35 nm silver nanoparticles. The result shows that at the same charge volume, the thermal resistance of the heat pipe with nanofluids is reduced by 10% to 80% compared with that of DI water at an input power of 30 W to 60 W. The results are compared with those of Wei *et al.* [82]. They show that the maximum reduction in the thermal resistance of the heat pipe is 50% for 10nm silver nanoparticles and 80% for 35nm silver nanoparticles.

Chein *et al.* [15] numerically tested the performance of nanofluids as coolants in silicon micro channels. The nanofluids they used were water suspensions of Cu nanoparticles at various particle loadings. They found that the performance of the micro channel heat sink was greatly improved due to the increased thermal conductivity and thermal dispersion effects, as well as that the presence of the nanoparticles in water did not cause much pressure drop due to the small volume fraction of the solid particles. Ma *et al.* [83] were the first to develop an ultrahigh performance chip cooling device called the nanofluid oscillating heat pipe. The conventional heat pipe with an oscillating motion generated by the variable frequency shaker dramatically increased the heat removal rate in capillary tubes. However, the use of the mechanically driven shaker limits these applications to chip cooling in practice.

Military applications

Military hardware both mechanical and electrical devices dissipates a large amount of heat and consequently requires high heat flux cooling fluids having sufficient cooling capacity. Nanofluids have the capability to provide the required cooling capacity in such applications, as well as in other military applications, including submarines and high power laser.

Medical application

Nanofluids are now being developed for medical applications, including cancer therapy. Iron based nanoparticles can be used as delivery vehicle for drugs or radiation without damaging the neighboring healthy tissues by guiding the particles up the blood stream to the tumor locations with magnets. Nanofluids could be used to produce higher temperatures around tumors, to kill cancerous cells without affecting the nearby healthy cells [84]. Nanofluids could also be used for safer surgery by cooling around the surgical region, thereby enhancing the patient's health and reducing the risk of organ damage.

Nanofluids are currently expensive, partly due to the difficulty in manufacturing them. The development of new synthesis methods is necessary to make nanofluids more affordable before they will see wide-spread applications.

Conclusions

The present review is a comprehensive outlook on the research progress made in the thermal enhancement process using nanofluids. The aim of the nanofluid research is to develop new methods to augment the synthesis method, novel equipments for measuring the thermophysical properties and synthesize nanofluids with excellent transport properties. The size of the nanoparticles plays an important role in improving the heat transfer properties. The dispersion behavior of nanoparticles improves, if the nanoparticles can be prevented from agglomeration using appropriate surfactants. The mechanism of the temperature dependence of thermal conductivity continues to be a prime research area, where experimental findings are used to substantiate theory and applications.

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Nomenclature

A – cross-section area, [m^{2}]
C_p – specific heat, [Jkg^{-1}K^{-1}]
D – inner diameter of the tube, [m]
d_p – nano particle diameter, [m]
g – acceleration due to gravity, [m^{2}s^{-1}]
h – heat transfer coefficient, [Wm^{-1}K^{-1}]
k – thermal conductivity on nanofluid, [Wm^{-2}K^{-1}]
L – length of the test tube, [m]
Nu – Nusselt number, [–]
Pe – Peclet number, [–]
Pr – Prandtl number, [–]
Δp – pressure drop, [Pa]
Q – heat transfer rate, [W]
Re – Reynolds number, [–]
T – operating temperature, [K]
U – overall heat transfer coefficient, [Wm^{-2}K^{-1}]
u – mean velocity, [ms^{-1}]

Greek symbols

α – thermal diffusivity, [m^{2}s^{-1}]
λ – friction factor
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – density, [kgm^{-3}]
ϕ – volume concentration, [%]

Subscripts

b – bulk temperature
d – particle
e – effective
f – base fluid
i – inside

lm	– log mean
m	– base fluid matrix
nf	– nanofluid
o	– outside
w	– wall temperature

Acronym

EMT	– effective media theory

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